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Design of a sub-13-fs, multi-gigawatt chirped pulse optical parametric amplification system

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ABSTRACT We present a design for phase-locked chirped pulse optical parametric amplification of ultra-short pulses based on Ti:sapphire. A realistic description is given by measuring the oscillator pulse (11.6 fs, 4 nJ) with SPIDER and numerically propagating it through the whole chirped pulse amplification system. The interaction is modeled with a full three-dimensional code and compression is ray-trace optimized to yield 12.7-fs, 98-μJ pulses with 1 mJ of pump energy. The design is scalable in energy (e.g. 1 mJ with 10-mJ pump) and is exclusively based on commercially available components.

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1 Introduction

Many experiments, especially in high-field physics [1], require the reproducible ('phase-stabilized') generation of waveforms only a few optical cycles long, with properties such that they can be focused to intensities of more than $10^{14}\ \mathrm{W/cm^2}$. So far, the only approach to produce such few-cycle, phase-stabilized pulses is exclusively based on chirped pulse amplification (CPA) [2] in stimulated emission based systems and spectral broadening in gas-filled hollow fibers [3] with subsequent compression. Chirped pulse optical parametric amplification (CPOPA) [4, 5] is a very attractive alternative to overcome the power limitations of those systems. However, all theoretical studies have modeled the three-wave interaction with oversimplified, idealized Gaussian or square pulse envelopes and refrained from taking any measured chirped pulses into account.

In this article, we present a numerical study of phase-stabilized amplification of ultra-short pulses from a 1-kHz Ti : sapphire oscillator based on CPOPA, which we have recently demonstrated experimentally [6]. We have here tried to most realistically model a complete CPOPA system and we have found that it is crucial to take all components of the amplification system into account. The model parameters are exclusively based on measured values from available components, which makes such a system feasible at the present time.

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The achieved values are currently not superior to state-of-the-art ultra-short-pulse laser systems based on gas-filled hollow fibers, but we expect that as soon as more powerful pump sources become available, CPOPA will quickly advance. For example, the model presented here predicts approximately 1 mJ of pulse energy for 10 mJ of pump by simple scaling of the beam areas.

Since parametric processes involve only transitions between virtual states, they are extremely attractive with the main features being: (1) an extremely high single-pass gain (up to 10^7), (2) broad gain bandwidths (more than 180 THz) [7], (3) virtually no thermal loading, (4) very short media (a few mm), making dispersion compensation simple and minimizing path lengths, and (5) aside from quantum noise, a phase-stabilized seed does not get disturbed by a non-stabilized pump since fluctuations go into the idler. The required pump intensity determines the stretching factor of the seed (to be efficient) for a given pump energy. Some of these features have been previously exploited, but not a combination of all of them. The major obstacle has been finding a pump source capable of delivering sufficiently short, high-energy pulses.

Even so, with existing technology, two extreme features have been demonstrated: multi-terawatt-level amplification with long pulses from low repetition rate glass lasers [8, 9] and ultra-broadband amplification to the nanojoule level from a white-light seed [10–12]. We recently reported an experimental realization of the system modeled here, with pulse energies and durations in good agreement with the numerical simulations, and experimentally verified the carrier–envelope offset (CEO) phase preservation in the CPOPA process [6].

2 Chirped pulse optical parametric amplification (CPOPA)

A schematic of the proposed system is shown in Fig. 1. We model a system based on a phase-stabilized oscillator (FemtoPower M1, Femtolasers GmbH), which delivers 11.6-fs (FWHM) pulses at 800 nm, at a repetition rate of 76 MHz, with an average power of up to 850 mW. A crucial component of any CPOPA system is the pump, whose pulses are required to be temporally synchronized with the seed pulses with jitter of less than a fraction of the pulse duration. Therefore, for this feasibility study, we consider

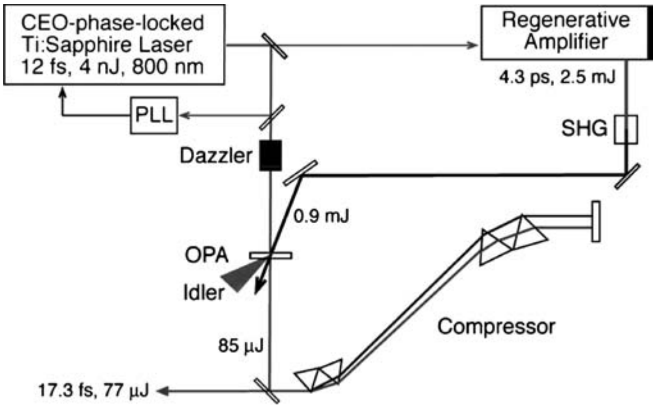

FIGURE 1 Schematic of the experimental setup

	GDD [fs^2]	TOD [fs^3]	4OD [fs^4]
DAZZLER	14 159.6	9343.7	5289.2
BBO	201.6	142.5	– 29.3
Dry air	85.2	39.6	4.6
TOD mirrors	1875.0	50 000.0	125 000.0
Sum	16 321.4	59 525.8	130 264.5
Compressor	– 16 321.4	– 58 158.1	– 144 893.2
Total	0.0	1367.7	– 14 628.7

TABLE 1 Dispersion balance sheet

a 1-kHz regenerative amplifier capable of delivering pulses of either 30-fs or 5-ps (FWHM) duration at 800 nm, with energies of up to 2.5 mJ. Seeding the regenerative amplifier with part of the seed for the CPOPA ensures synchronization, but results in a complex pump source and pump pulses – after frequency doubling – at 400 nm, whereas maximal phase-matching bandwidth in β-barium borate (BBO) occurs for pump wavelengths around 510 nm. In order to determine the crystal length, stretch factor and necessary pump-pulse characteristics, we work backwards: for a given pump wavelength, energy and pulse duration, we determine the beam diameter necessary to achieve the required pump intensity for good parametric amplification. This sets the crystal length, determines the walk-off and sets the required seed stretch factor. The compressor is then calculated to achieve the best possible recompression.

We only concern ourselves with a stretcher/compressor design that is based on bulk stretching and subsequent compression in a prism sequence, since previous measurements indicate that, with gratings, beam-pointing variations can severely deteriorate the phase lock [13]. The restriction to bulk materials limits the maximum feasible stretch factor of a 10-fs pulse to roughly 1000. This value is mainly determined by the ratio of group-velocity dispersion (GDD) to third-order dispersion (TOD), which is constant in the stretcher but varies monotonically for the prism sequence. For our model system, we include a DAZZLER (WB-800, Fastlite, Inc.) to permit final higher-order dispersion compensation. The DAZZLER crystal is highly dispersive, and is used as the stretching medium. Additionally, we include the dispersion introduced by the seed propagation through 4 m of dry air and 3 mm of BBO.

Performing simulations for different combinations of materials, we found that excellent passive compensation of the dispersion introduced by the DAZZLER can be achieved with a combination of LaK8 double prisms and 25 bounces on standard TOD mirrors (Femtolasers GmbH). In order to accurately model a prism compressor for any amplifier system at appreciable energy levels, the paraxial approximation with infinitely small beam diameters cannot be used. Hence we undertook full ray-tracing simulations for a collimated $1/e^2$ beam waist of 8 mm. We have verified experimentally that in LaK8 (WZW Optic AG), an 800-nm, 2.7-mJ beam of 30-fs pulses, with a waist of 8 mm, does not experience any spectral distortions. The double-prism compressor, designed for a band pass of 200 nm, consists of Brewster prisms, two of them with a side length of 50 mm and the other two of 150 mm. The apex separation of the small prisms is 60 mm, of the large prisms 540 mm and the separation between the inner prisms is 1500 mm. The individual prisms could be arranged independently to remove the remaining fourth-order (4OD) and higher-order dispersion, but the necessary placement accuracy is difficult to achieve in practice; also, because of the temporal distortions of the seed beam exhibited for different pump energies and timing, we suggest using the DAZZLER for ultimate fine-tuning dispersion compensation. Table 1 lists the calculated dispersion values for each system component.

3 Simulation results

The parametric amplification simulations are based on a full three-dimensional (3D) model [14] of the coupled wave equations that takes walk-off and dispersion to all orders into account. Parasitic second-harmonic generation (SHG), which can reduce OPA efficiency and distort the spectrum, was also included. As initial parameters, we take a single split-off oscillator pulse that we have measured using SPIDER [15], with the temporal profile as shown by the dotted line in Fig. 2a. The 4-nJ (300-mW) pulse is numerically propagated through the stretcher, up to the OPA crystal, and shaped to a 0.5-mm beam waist. The dotted line in Fig. 2b shows the stretched pulse profile with the corresponding seed spectrum given by the dotted line in Fig. 3a. For the given parameters, the crystal of choice is a 3-mm-long BBO crystal cut at $\theta = 29.2°$, with an internal non-collinear angle between seed and pump beams of 16 mrad. We consider two different pump pulses, as obtained from the regenerative amplifier: (1) an initially 30-fs-long pulse at 800 nm, stretched and frequency doubled to 5 ps, 400 nm (CP pump) and (2) a transform-limited (TL) 5-ps pulse at 800 nm doubled to 400 nm (TL pump). Both are assumed to have an energy of 1 mJ. The former is readily available but expected to yield a lower conversion efficiency, unless the required temporal sequence of spectral components between chirped pump and seed are accurately matched. The latter pump source is more demanding to construct but will give the highest conversion efficiency.

The amplified pulse spectra in Fig. 3a are normalized but contain a total energy after amplification of 98 µJ with the transform-limited (TL) and 47 µJ with the chirped (CP) pump pulse. Energy sharing between signal and idler is nearly even

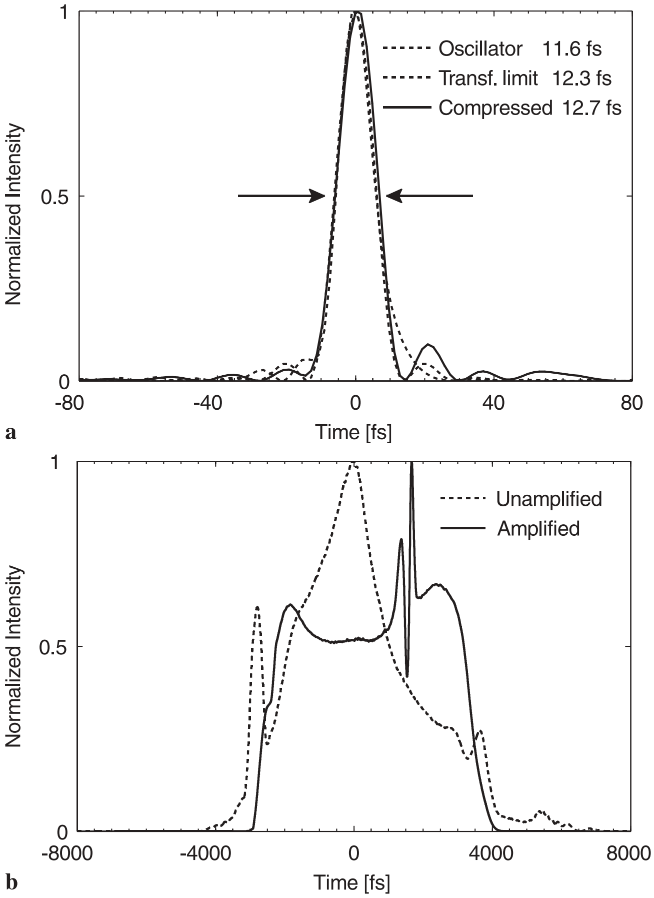

FIGURE 2 **a** Oscillator seed pulse as measured with SPIDER (*dotted*) and the recompressed amplified pulse after propagation through the complete amplifier system (*solid*). For a comparison, the transform-limited pulse is shown by the *dashed line*. **b** Stretched seed before (*dotted*) and after (*solid*) amplification in the CPOPA

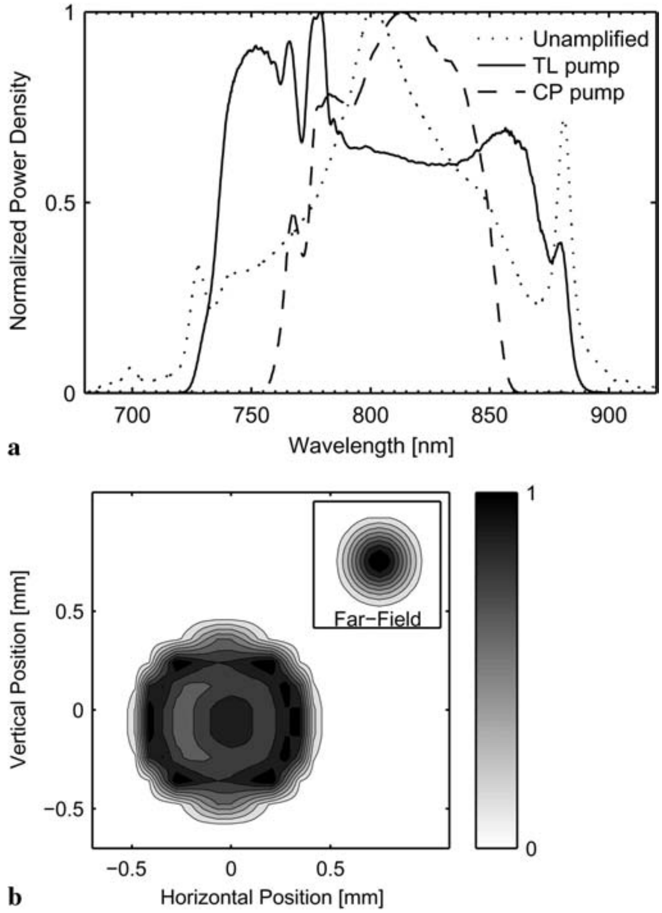

FIGURE 3 **a** Normalized spectra of the unamplified seed (*dotted*) and the amplified seeds are shown for pumping with a transform-limited (TL, *solid*) and a chirped (CP, *dashed*) pulse. **b** Amplified near-field seed beam profile for the transform-limited pump. The calculated far-field profile is shown in the *inset*

with 103 μJ in the TL and 49 μJ in the CP case, and the pump (1 mJ) depletion is found to be 21% (TL) and 11% (CP), respectively. The single-pass gain is 2.5×10^4 in the TL case.

Spectral and temporal shaping occurring during amplification with the TL pump are clearly visible in Figs. 2b and 3a. Parasitic SHG is responsible for the spectral structure in Fig. 3a. The Gaussian pump-pulse envelope results in shortening of the stretched pulse duration, visible in the solid line in Fig. 2b, which could be reduced using a longer pump pulse at the cost of reduced efficiency. At the same time the amplified spectrum is narrowed and flattened, resulting in a longer transform-limited pulse duration compared to the oscillator pulse. Some adjustments can be made by trading bandwidth for pulse energy due to the chirped seed temporal overlap with the pump pulse.

The resulting near-field beam profile is shown in Fig. 3b, with the slight asymmetry in the beam profile being due to walk-off. The far-field profile is shown in the inset. We used the emerging amplified far-field pulse to determine the prism compressor parameters. Figure 2a shows that good dispersion compensation is possible, with the transform-limited (dashed line) and recompressed (solid) pulses having nearly identical pulse durations of 12.3 fs and 12.7 fs. The difference arises from the remaining accumulated phase terms that are not compensated by the passive system (see Table 1), and could readily be eliminated by pre-compensation of the seed using the DAZZLER.

4 Conclusions

We modeled CPOPA of phase-locked ultra-short pulses from a Ti : sapphire oscillator and found that with excellent recompression (11.6 fs to 12.7 fs), single-pass amplification from 4 nJ to 97 μJ can be obtained even for a modest pump energy of 1 mJ. The single-pass gain bandwidth could potentially be improved by pumping in the green, whereas the efficiencies could be improved by temporally shaping the seed and pump pulses to resemble a square shape. We believe that our model is most closely related to a ‘real-world’ system since we have included measured pulse and material parameters, and undertaken 3D OPA simulations, ray tracing of the compressor and pulse propagation including dispersion from all components.

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